Multi-angle Imaging SpectroRadiometer (MISR) design issues influenced by performance requirements

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ABSTRACT

The design of an Earth remote sensing sensor, such as the Multi-angle Imaging SpectroRadiometer (MISR), begins with a set of science requirements and is quickly followed by a set of instrument specifications. It is required that the sensor meet these specifications across the image field, over a range of sensor operating temperatures, and throughout mission life. In addition, data quality must be maintained irrespective of bright objects, such as clouds, within the scene, or out-of-field glint sources. During the design phase of MISR, many refinements to the conceptual design have been made to insure that these performance criteria are met. These design considerations are the focus of this paper. Spectral stability with field angle, scene polarization insensitivity, and UV exposure hardness have, for example, been enabled through a telecentric optical design, a gaussian shaped filter spectral profile used in conjunction with a Lyot depolarizer, and contamination prevention through considerations in material choices and handling procedures. Spectral, radiometric, and MTF stability of the instrument assures the scientific community that MISR imagery can be used in aerosol, hi-directional reflectance distribution function (BRDF), and cloud studies without constant review of the instrument's health and operating conditions during data acquisition.

1. INTRODUCTION

The Multi-angle Imaging SpectroRadiometer (MISR) has calibration and performance requirements which are challenging as compared to those specified for previous generation remote sensing systems. The instrument is to measure incoming spectral radiance to within 3% in absolute units of energy. (MISR will be calibrated to Système International standards[1], or "S1" units, which are those adopted and recommended by the Eleventh General Conference on Weights and Measures held 11-20 October 1960 in Paris, France,) To accomplish this calibration a comprehensive set of tools are to be utilized, including detector-based radiometric standards, an on-board calibration system which illuminates the entire camera geometric and stray-light fields-of-view, and plans to acquire surface and atmospheric data during an "overflight calibration". The latter uses a computation of incident radiance, using the field measurements or aircraft underflight data, and provides a calibration independent of that determined preflight or by using the on-board calibrator. This reduces calibration uncertainty, as systematic errors present in each technique are averaged out.

Calibration activities, like those described above, are those conducted to derive quantitative descriptors of the instrument features, and are needed within MISR data processing algorithms. Thus, the radiometric, spectral, camera pointing directions, and camera fields-of-view are measured at the end of the camera development phase. Such attention to sensor calibration would bc.pointless, however, if the instrument suffered temporal instabilities, image history effects such as memory of bright objects, or stray-light contamination of a scene under study. For this reason many design features are incorporated into MISR to insure instrument performance over the anticipated range of sensor operating conditions and scene types. They come to the attention of the design engineer through the instrument science specifications[2], and are verified either by test or analyses before instrument delivery to the spacecraft integrator. Such an instrument characterization is needed to give assurance to the data user that the MISR data products are valid to within the stated uncertainties, irrespective of pixel position within the sensor, sensor operating temperature, time since launch, or nature of the scene under evaluation. A select number of these design features arc reviewed here, in greater depth than that covered in the MISR instrument overview paper presented previously[3].

2. INSTRUMENT STABILITY

2.1 Contamination

MISR is required to maintain a 0.5% radiometric stability during a month, and 2% per year. These values are needed to that calibration coefficients applied as a result of one study are appropriate to data sets acquired at different points in time. If care is not taken, the effects of contamination could be the biggest potential source of instrument instability. Of particular concern are the photoactive chemical species which may collect on the camera optical elements, and which may brown and become opaque upon exposure to *W* irradiation. During the course of an orbit, the MISR C and D camera front elements are directly illuminated by sunlight, for a period of about four minutes per orbit. Figure 1 depicts this situation, for the D-aft camera, the camera for which the illuminated area is greatest in extent. In addition, each time the calibration panels are deployed, all cameras are exposed to *W reflected* sunlight. The accumulative exposure to this latter energy source is about 100 hours over the mission life.

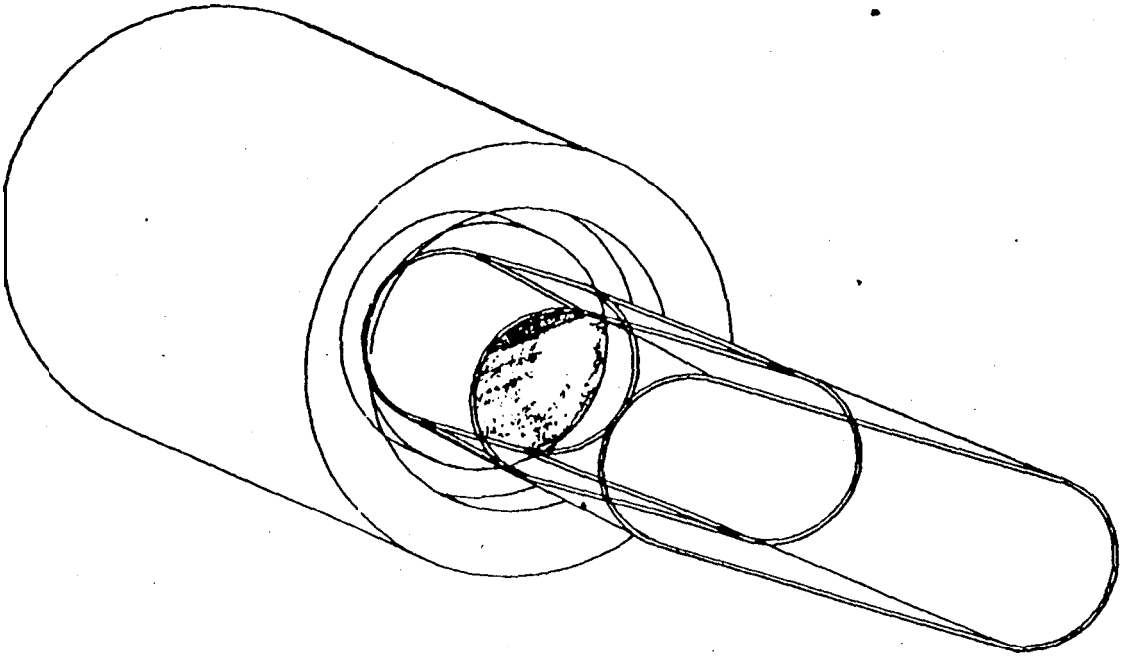

Figure 1. Fraction of front element exposed to *W* illumination during polar region passage. Shown is worst-case D-aftward looking camera.

Because of the potential for contamination-induced degradation of the optical throughput, the MISR team is taking great care to insure the instrument is contamination free. External surfaces are manufactured such that they are cleanable, with ethanol alcohol, or by some surface-specific cleaning technique. Materials used for the instrument must be approved by the materials engineer and must be free from the potential to crack or produce particles, be minimal] y outgassing, and are designed to withstand thermal bakeout procedures.

An additional self-protection measure is the plan to keep MISR under a positive pressure flow of gas from a liquid nitrogen tank. The gas is faltered and dried to military and JPL specifications, and the instrument is designed to withstand 200% of this gas pressure without damage. Venting of the effluents will be away from the contamination sensitive surfaces.

The accumulation of particulate and molecular contaminants must be controlled to the extent that an insignificant change in optical, throughput results. The effects of accumulation of contaminants duc to thrusted exhaust plumes must also be considered. Analyses to date has demonstrated that this effect will be small. The propellant used by the spacecraft will never be directed into the MISR line-of-sight, except through re-emission from other surfaces. Calculations show that this re-emission rate is small, As an added

precaution, however, MISR will be equipped with an instrument cover which can be deployed should this be determined necessary at some later date.

2.2 Environmental exposure

Another area of study relevant to camera stability is the effect of the in-orbit environment. In general, electron and proton particulate, and UV irradiance are known to induce transmission changes in optical glass. Specifically, ionization can occur when energy sufficient to overcome the energy gap is provided to an electron within an optical glass. This freed electron can, in turn, create a defect center with increased absorption. Likewise, these environmental elements can create damage centers in photodetectors. The effects of atomic oxygen also have to be addressed. For many of the components used within MISR, there is no previous performance data relevant to our particular mission dosage levels. Indeed, there is no flight data at all on Spectralon, used as the MISR calibration target.

The stability of several candidate MISR glasses has now been tested in an environment simulating electron and proton exposure levels throughout the EOS mission[4]. From these tests it has been determined that there is no need to be limited to cerium-doped, radiation resistant glasses, The detectors used within the MISR focal plane have likewise undergone radiation testing. It is found that there is an increase in dark current with exposure, but that the MISR signal-to-noise requirements are still met, even assuming end-of-life dark current values. Finally, simulations of the proton environment and it's impact of Spectralon have eliminated particle radiation as a source of concerns. (Protons are believed to be more damaging than electrons, so electron testing was not conducted.)

Atomic oxygen exposure is not believed to be a problem for the MISR instrument[6]. The only optical surface exposed directly to the ram spacecraft direction is the North pole calibration plate, that is the forward plate which swings aftward over the North pole to enable calibration of the aftward viewing and nadir cameras. The worst case atomic oxygen erosion depth has been calculated to be 6 nm, over the 100 hours of panel use. As the peak-to-valley depth of Spectralon is naturally 30 μm or more, the erosion depth is less than 0.02%. It is not expected that this small amount of erosion will effect the optical properties of Spectralon.

With these studies, and others planned in the near future, we can verify that the MISR design is robust against the effects of the in-orbit environment.

2.3 Filter design

The degradation of camera throughput, as created by contamination and environmental exposure effects can be corrected for with time, provided that the instrument eventually becomes stable, and provided the system SNR requirements can still be met. If these criteria are met, then a new radiometric calibration can be established, in-flight, and the science needs can be met. The problems created by undetected spectral shifts, however, are of a different nature. Without knowing the ncw bandpass profile it is impossible to restore the instrument calibration to the same level of accuracy as that provided in the absence of any spectral shifts. There has been much published in the literature, for example, on spectral shifts noted during the Landsat program[7]. On the Thematic Mapper (TM) there were observed shifts in radiometric sensitivity measured in going in and out of vacuum in prelaunch tests. These "vacuum shifts" were believed related to the spectral filters. Similar changes were noted shortly after launch. More recently engineers have measured the transmission of witness samples of the TM filters used on Landsats 4-6 in and out of vacuum, and have observed bandwidth changes on the order of 5 nm. These shifts could account for the observed vacuum shifts. Landsat-7 will use the newer filter technology.

Prior to the 1980's coatings were used which lacked resistance to moisture and the effects of handling. Currently some of the best filters made for narrow-band applications, and requiring stability over time, rely on ion assisted deposition (IAD). (Not all interference layer materials are inherently instable, so it would be misleading to infer a given filter is necessarily instable without this technology.) In this process an ion source is utilized during plasma deposition of the oxide coatings, This allows for compactness in the layer coating, and this in turn precludes the layer from the adverse consequences of moisture absorptance. As well as packing density, adherence and other factors arc improved. The durability of filters produced using IAD technology has

been demonstrated as they have been cycled to 300°C, and submersed in liquid nitrogen, without detectable effects. Other examples of IAD stability tests follow.

In 1988 BARR Associates produced for the Research in Astronomy (AURA) in Tucson, Arizona an IAD filter of 8 A width and 679 nm center wavelength. Three other filters were produced at the same time. AURA devised a test consisting of temperature cycling from 26 to 46°C and back, seven times daily. After three years of testing the conventional filters had shifted by 2-3 A, and the IAD filter had not shifted to within IA uncertainty.

Other in-house testing at BARR has verified wavelength stability. A 340 nm filter with an 8 nm bandpass had been made with the Ta_2O_5 IAD process, After 5300 hours of exposure at 95% RH and 65°C, the center wavelength was found to be stable, to within 0.-15 nm measurement uncertainty, as was the FWHM stayed the same (to 0.01 nm uncertainty). The measurements were taken with a Cary 2400 with an assumed wavelength error of ±0.1 nm.

3. SPECTRAL UNIFORMITY

3.1 Telecentric optical design

There are many design objectives which have driven the MISR optical layout. It is desirable, for example, to minimize the number of optical elements, as well as the weight and volume of the lens. Materials must be selected which are stable in the on-orbit environment. In addition, there are many image fidelity requirements. These include acceptable image distortion and MTF, relative illumination uniformity across the focal plane for a uniform input, and athermalization to assure focus and a constant focal length with temperature. The requirement to accept only slight deviations in center wavelength and bandpass along an array is made, however, not to assure image fidelity, but rather data product fidelity. That is, without this requirement the departure in these parameters from on-axis values could yet be determined through modelling and calibration. Each image pixel would therefore provide art equally accurate measure of the scene radiance with which it observes. Here, however, the wavelength at which the radiance is reported would vary along the cross-track image swath. The science user would inherit an excessive data interpretation problem. It would not be clear if differences in retrieved reflectance were a result of spatial, or spectral scene reflectance differences.

The MISR spectral specifications include a requirement to permit no more than a ±2.0 nm shift in central wavelength or deviation in bandwidth across the array, for the 0.865 nm worst case band. (The allowable shift in center bandwidth is ± 1.0 nm for Bands 1 and 2, and ±1.5 nm for Band 3.) These requirements were not initially met in the original MISR optical layout. Here a Double Gauss configuration was chosen, a six element design which is a powerful lens design format featuring good distortion control including low chromatic and spherical aberrations. The main difficulty with this traditional telescope design was it’s inability to meet the wavelength uniformity specification. The design was estimated to produce a 2 to 4 nm shift across the focal plane, for Bands 1 and 4 respectively. The current design, shown in Figure 2 for one of the four MISR camera designs, is nearly telecentric in image space. There is only a 3° shift in the cone angle of illumination, as compared to that for on-axis illumination. The design is achieved through use of an added seventh element which images the exit pupil at infinity.

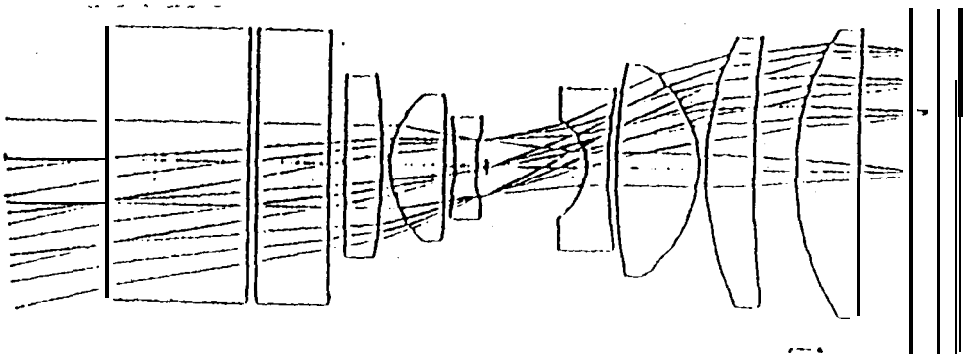

Figure 2. Telecentric optical design for Camera A design

The undesirable spectral shift in the original optics design was a result of varying incidence angle across the filter interference coatings. For interference filters in general there is a shift toward shorter wavelengths with increasing angle of incident of the impinging light. The magnitude of this effect is related to the effective index of the multi-layer coating. This index lies between the refractive indices of coating materials. For a given design, the effective wavelength shift is a function of the light cone used during imaging, The result for the MISR F/5.5 system is shown in Figure 3, solid line. The dashed line represents the spectral shift due to the 3° shift across the focal plane. It is found that the shift is 0.35 nm. This effect is seen as a wavelength shift with position on the focal plane, and is well within the MISR science specification. This analyses was done separately on the blocking-layers, those layers deposited so as to allow the out-of-band spectral light leaks to be controlled. Almost no change was noted for these layers alone.

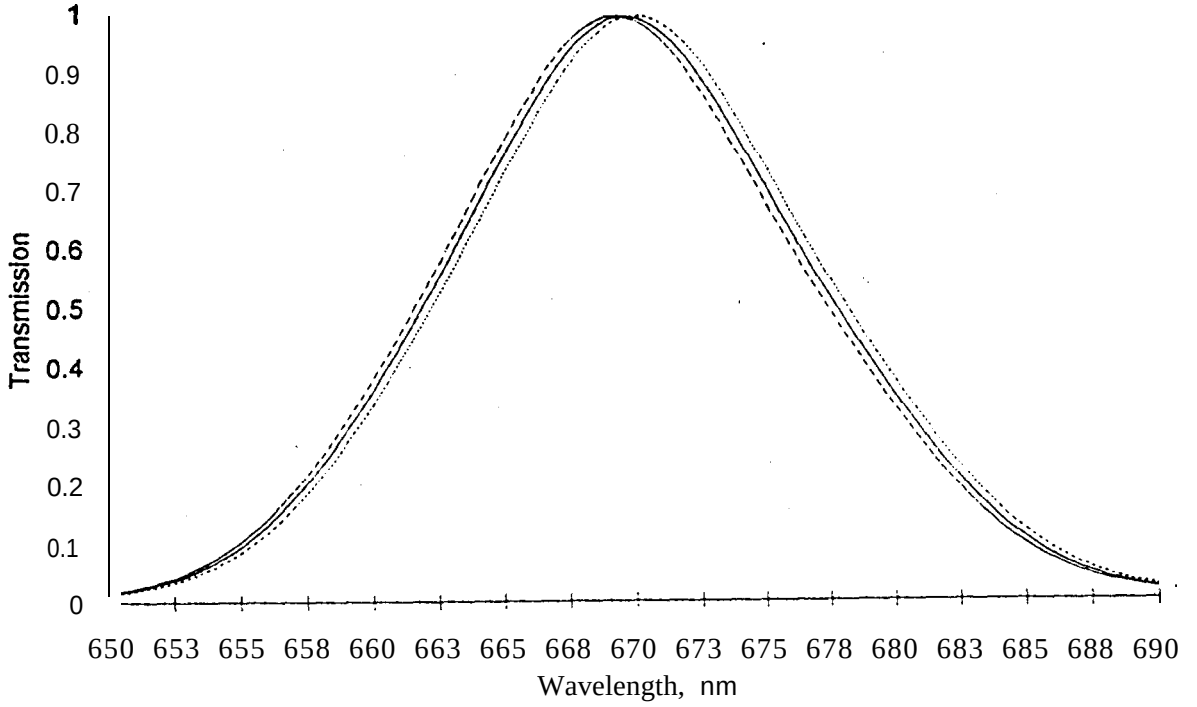

Figure 3. predicted filter spectral throughput for MISR F/5.5 system. Solid line in is filter output as viewed by an on-axis pixel, dashed line is edge-of-field response.

Other sources of filter nonuniformities across the array are due to the manufacturing process. There area number of process-related factors that can effect the uniformity. Among them are geodetical configuration of the parts during deposition and thermal gradients across a part during deposition. Both of these are affected by tooling, heating techniques, mounting techniques, photolithography stencils, and others, With current control capability, the uniformity can be controlled to within 0.5 nm across the array, and to within 0.75 nm between filters. Another insignificant contributor to spectral shifts is the effects of temperature. Commonly used films suffer from changes in refractive index and layer thickness, which in turn changes the optical path length. This typically causes a shift toward shorter wavelengths with a decrease in temperatures. With IAD oxides the temperature coefficient is less than 0.005 nm per degree C. This is a factor of five less than traditional coatings. Temperature induced spectral shifts are therefore believed not to be a problem for MISR. The geometric effect of wavelength shift with angle is found to be the only significant contributor to spectral nonumiformit y either across the filter, or from one filter to another.

4. RADIOMETRIC ACCURACY

4.1 **Contrasting targets**

The MISR science team is interested in the effects of the optical point-spread function (PSF) on the radiometric accuracy and frequency response of each camera design. The PSF includes the effects of diffraction, optical aberrations, scattered light, charge diffusion within the CCD, and CCD charge transfer inefficiency. (Scattered light is defined here as that which originates from

sources within the camera field-of-view.) In order to verify radiometry accuracy in the presence of these effects, the MISR instrument requirements have defined two scenes which typifies situations believed to be problematic. The first scene consists of two half-planes of 5% and 100% reflectance. The radiance on the dark side is specified to be accurate to within 2%, at a point 24 pixels from the boundary. The second scene consists of a 5% reflecting region, 24x24 pixels in size, surrounded by a 50% reflecting background. The retrieved radiance for any pixel within the dark region, is specified to be no more than 2% of the radiance measured in the absence of the background. It is noted that the instrument requirements do not specify that the radiometric accuracy must be achieved through instrument 'design only. It is undetermined at this point if MISR will construct algorithms to correct for PSF over contrasty scenes, It is likely that if this technique is developed, however, it may only be applied to a limited number of scenes of particular interest to the science community.

The above specifications dictate that the MISR engineering staff put considerable effort into characterizing the radiometric accuracy for these two scene types, The approach actually to be used, however, is to model the PSF at various points both within and out-of the camera geometric field-of-view. This latter approach is preferred, in that this information can be used to predict the radiometric accuracy for any scene contrast. To accomplish this task many math models will be used, The optical design code will model the predicted PSF due to diffraction and optical aberrations. These results are combined with those from a scatter-analyses code, and the degradations expected due to detector effects. These data are used to construct the system response to the contrasting scenes described above.

A limited amount of testing will also be done to verify the above model analyses. That is, the system PSF will be characterized at a limited number of field positions. This will confirm the model PSF computed as described above. Although it will not be possible to actually construct a target to represent to two scenes described above, a close representation will be provided. The modelling effort will then predict the radiometric error for this test target, thus allowing a comparison of model and actual test data.

4.2 **Stray light**

It is required that stray light from out-of-field sources be rejected such that the radiometric accuracy is preserved for a scene under study, To accomplish this task MISR has made usc of a stray-light code, and modelled the PSF for out-of-field sources, This activity has led to some design changes within the camera. The out-of-field PSFS will again be computed for the new design, thus estimating the stray-light effects for our final system.

The above model analyses will be verified using point sources to 5° outside the camera FOV. Because of constraints imposed by our thermal vacuum chamber, this is the limit of the test. The engineering team, therefore, is making full use of analyses to verify the instrument requirements.

4.3 **Polarized incident radiance**

The accuracy with which MISR measures an incident radiance field must be maintained, irrespective of the incoming state of polarization. This is not necessarily guaranteed for a system, as the amount of light reflected at each optical interface depends on this state. This effect is described by the Fresnel reflection coefficients, and results in a polarization dependent transmittance for the system. It is not possible to calibrate the sensor for this effect, as the scene polarization properties are not simultaneously measured or otherwise known,

The MISR polarization requirement implies that the detector output, resulting from a stimulus of arbitrary plane of polarization, shall not deviate by more than 2% over that measured while viewing an unpolarized stimulus. This allowable error is a sizeable portion of the total radiometric error budget of 3%. *The* MISR conceptual optics design, however, did not meet this specification. In this design a single layer MgF_2 anti-reflection coating layer was assumed, The layer increased transmission and decreased diattenuation. Diattenuation is defined as $D=(T_p-T_s)/(T_p+T_s)$, and describes the maximum dependence of system transmittance on the incident polarization state. Here T_p and T_s arc the transmission coefficients for p and s polarized light (light polarized parallel and perpendicular to the plane of incidence). For an ideal system D=O.

The current design replaces the single layer MgF_2 anti-reflection layer with a six element stack. With this the lens diattenuation decreases from 20% to 3% at the worst case wavelength and field angle. More significant, however, is the performance improvement gained through use of a Lyot depolarizer. This added optical element is used in conjunction with a gaussian spectral band shape, hence the MISR requirement of a gaussian filter design. For ideal performance the system response would be gaussian in frequency, not wavelength. It has been determined, however, that requiring the filter to be roughly gaussian in wavelength is sufficient. The transmittance of an individual filter will approximately correspond to $\tau_{g,\lambda}=\tau_g \exp(-((4 \ln 2)(\lambda-\lambda_{c,g})^2/(\Delta\lambda_g)^2)$, where τ_g is the peak transmittance, $\lambda_{c,g}$ the wavelength at peak transmittance, and $\Delta\lambda_g$ the full width half maximum (FWHM) of the band.

A Lyot depolarize? consists of two birefringent plates rotated by 45° relative to each other. The Lyot depolarizer to be used by MISR will be composed of MgF_2, which has a high birefringence, and will be approximately l", for the camera A design, and 1/2" - long for the D-design. The added thickness of the crystal needed for the nadir camera is a result of the larger field angles covered by this lens, and greater diattenuation. The two elements are separated by an air gap, rather than optically contacted. Thermal gradients may separate optically contacted elements, resulting in destructive interference effects. These plates introduce a large retardance variation across the spectral band of the instrument effectively depolarizing the incident light. The ability of a Lyot to provide an unpolarized emerging field is dependent on the "degree of coherence" of the spectral band in question. This is basically a Fourier transform of the incoming spectral signal, and is not monotonic for the conventional square-band shape. Other disadvantages of using a square-band profile with the depolarizer is the increased sensitivity to temperature, the birefringencc being a function of temperature.

With the Lyot, a 100% linearly polarized beam would be scrambled to yield an exiting field of 5% polarization, including Fresnel losses at the front surface. Allowing for a 5% diattenuation of the lens system, and a worst case filter diattenuation of 10%, the radiometric error of the system is predicted to be 0.5%. It is noted that the filter need not be highly non-polarizing, as the detector is the only remaining component, and it is polarization insensitive.

In reality, very few scenes will be 100% polarized. This could happen, for example, while viewing an ocean scene, on a clear (aerosol) free day. The radiometric accuracy requirement, therefore, is now thought to be easily achieved. It is also required that a relative radiometric accuracy of 0.5% be achieved using a single camera and color channel. As it is unlikely that a scene will be composed of elements which differ by 90° in polarization, this criteria will be met at the 1σ confidence level.

4.4 Cloud and bright target saturation

Many of the performance specifications placed upon the MISR instrument require attention to design details within the detector and electronics subsystems. Several problems associated with Landsat-4 and -5 related to electronics are discussed in Kieffer et al.[9]. These included unequal population of digital bins due to non-uniform widths of successive voltage increments in the analog-to-digital converter (ADC), scan-direction dependent level shifts, overshoot at high contrast boundaries, an offset after scan of a bright image that lasted up to 800 pixels, and high-frequency noise. It is the attempt of the MISR design team to avoid these undesirable features in the design, and verify the instrument performance in the verification phase of the instrument build.

The MISR CCD will be designed and fabricated based upon standard 3-phase, 3-poly, n-buried channel, silicon detector technology. The CCD will consist of four independent line arrays each with its separate electronic shutter and output amplifier. A schematic of the CCD architecture, in cross section, is presented in Figure 5. This drawings can be referred to in the description of blooming and saturation control. These undesirable effects may be created if a large signal, such as that from an ocean glint or bright cloud, were to be viewed.

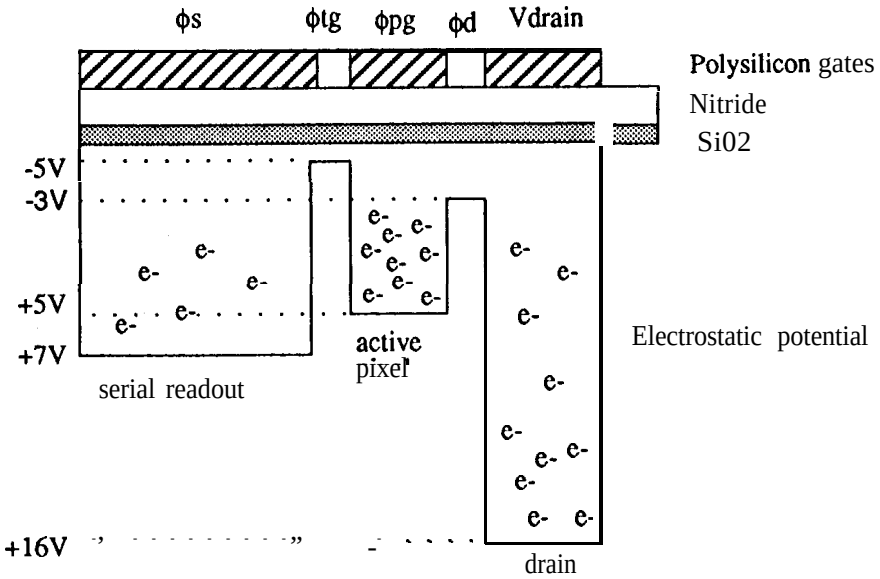

Figure 4. Detector biasing during charge integration.

The process of signal detection and collection begins when the transfer gate, φtg, and dump gate, φd, are biased low. Here a potential well is created under the photogate region, φpg, which is biased high. The φtg and φd regions act as barriers which prevent charge from spilling into the surrounding regions. If the capacity of the active pixel region is exceeded, blooming is prevented in the serial direction by the selective biasing of φtg and φd (to ~-5V and -3V respectively), that is φtg is set more negative than φd. Once the active pixel is filled, spillage will flow towards the drain region, Vdrain, and not into the serial readout registers φs2 and φs3. Saturation would only occur if both the active pixel and drain were filled. In the lateral direction, between pixels, the charge is confined by channel stops constructed from thick field oxide.

The capacity for blooming and saturation control was designed to absorb signals of at least 10^5 times fullwell without saturating the device. It is noted that large signals maybe encountered if a direct specular solar reflection, such as that due to ocean glint, is observed. Such an intensity would be tens of thousands of times greater than that observed by a bright but perfectly diffuse region of a scene. This design has been verified by testing of a prototype detector, It is expected that if the serial register does saturate, that the region will return to the normal dark current level within one or two line times. In addition, the electronic signal chain is equipped with a clamping circuit, to prevent any signal extremes from incurring damage to the back-end electronics.

The MISR instrument specifications state that if blooming occurs due to a signal between one and ten times the detector full well, that pixels at a distance ≥ 8 pixels shall be unaffected, This limits the undesirable effect no greater in size than eight unaveraged pixels. Design and testing efforts to date suggest that this requirement will be easily achieved.

4.5 **Electronic signal chain**

A brassboard assembly of the MISR A-camera design, including focal plane and signal chain electronics has been complete. Through test of this early prototype, the MISR team has begun to verify that the flight camera electronics design is achieving its performance specifications.

The CCD pixel data are clocked out in serial fashion, and fed into a preamplifier which lowers the impedance and acts as a buffer. This signal is fed into a signal chain which uses a "coherent double sampling" technique to control noise. Basically, as the CCD signal is read, a sampling circuit is used which measures the diffcrcncc between signal and ground. Synchronous sampling is key

to reducing noise between this read and that of the clock signals. CCD white noise is also faltered at this position. From here the signal it sent into the analog to digital converter (ADC). MISR will use a 14 bit ADC. The least significant bit of art ADC is known to have a noise uncertainty of 0.3 bits. By truncating the signal to 13 significant bits, MISR avoids this source of ADC error.

One source of noise within the electronics chain is the Constantine wire used for the ground return. This material was selected for its thermal properties, and has a higher impedance than other materials. These wires must be kept short to minimize noise within the system. All totaled, the noise allocation from these sources is expected to be about 40 electrons. This is insignificant as compared to our ADC sampling interval.

The predicted sources of noise for a MISR camera are depicted in Figure 5. Shown are both the components of noise and total noise, Nt, as a function of equivalent reflectance, p, for Band 1 of an A camera. Noise differences between camera design and spectral channel are insignificant. The limiting noise if found to be photon (shot) noise, Np, although electronic noise, No, is non-negligible at low reflectance. Due to square-root encoding, the quantization noise, Nq, does not become a limiting noise factor. The instrument science requirements state that the SNR to be achieved is 700, 600, 450, 300, 100, and "best possible" at equivalent reflectance values of 1., 0.7,0.5,0.2, 0.02, and 0.01, respectively. (To translate the SNR requirement vs. equivalent reflectance into SNR vs. radiance, an overhead exo-atmospheric sun is assumed which illuminated a perfectly diffuse panel, at the stated reflectance value.)

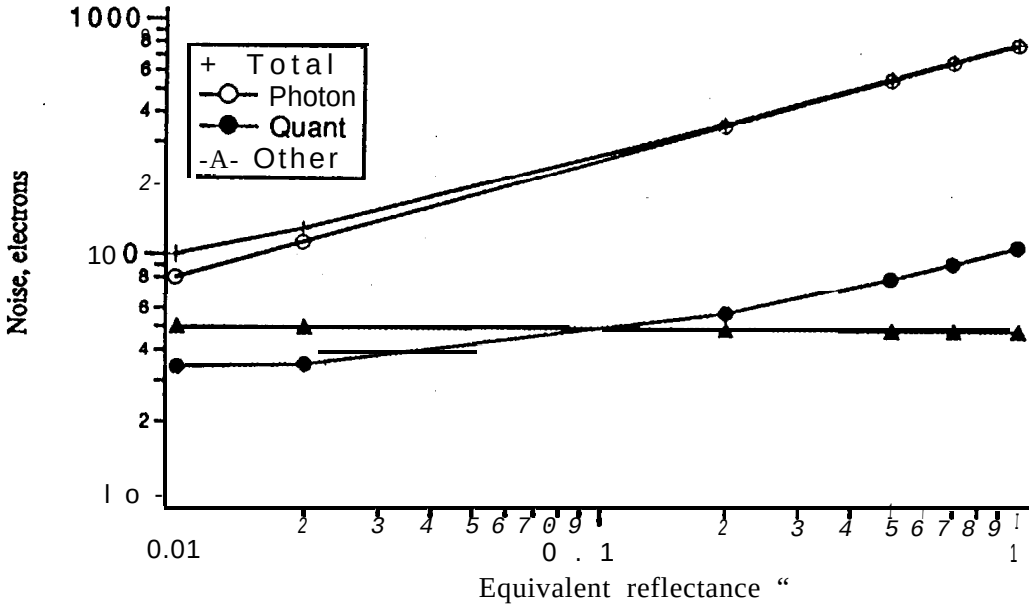

Figure 5. Noise sources for MISR camera.

5. CONCLUSIONS

The MISR instrument performance specifications have been produced to assure the data user and scientific community that MISR will provide high fidelity data sets even under adverse conditions such as high contrast scenes and varying input states of polarization. It is believed at this point in time that MISR will achieve these performance requirements. In addition to the build of the engineering model, and following flight hardware, the MISR team is currently involved in detailed planning of the verification test phase of the program.

6. ACKNOWLEDGEMENTS

We wish to thank all the members of the MISR design team for their contributions towards the instrument definition and the material presented in this paper. These include David Diner, principal investigator, Elmer Floyd, instrument manager, Larry Hovland,

instrument engineer, Daniel Preston, filter specifications and testing, Richard Rainen, materials selection, Daniel Taylor, Glenn Aveni, and David Guarino, contamination. A special thanks is extended to Frank Woodbury and his colleagues at BARR Associates, for providing the material used within the filter discussion. The research described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

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